

CATHODIC PROTECTION/PARTIAL COATINGS
VERSUS
COMPLETE COATING in BALLAST TANKS-FIVE YEAR REPORT

NOVEMBER 1987

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FOREWORD

This research project was performed under the National Shipbuilding Research Program. The project, as a part of this program, is a cooperative cost shared effort between the Maritime Administration and National Steel and Shipbuilding Company. The development work was accomplished by Associated Coatings Consultants under subcontract to National Steel and Shipbuilding Company. The overall objective of the program is improved productivity, and therefore, reduced shipbuilding costs.

This study has been undertaken with this goal in mind, and has followed closely the project outline approved by the Society of Naval Architects and Marine Engineers' (SNAME) Ship Production Committee.

Mr. James R. Ruecker of National Steel and Shipbuilding was the R&D Program Manager responsible for technical direction and publication of the final report. Program definition and guidance was provided by the members of the SP-3 (Formerly 023-1) Surface Preparation and Coatings Committee of SNAME. Special thanks is given to Mr John Peart for providing technical direction and editorial assistance.

EXECUTIVE SUMMARY

Ship ballast tanks are one of the most costly items of new ship construction. In addition, ballast tanks are one of the most severe corrosion areas during ship operations. The SP-3 Panel of SNAME recognized these problems and selected a research and development project to investigate alternate, cost effective corrosion control solutions. Four approaches were originally selected for mock-up ballast tank testing and 20 year life cycle cost analysis. A new coating system was added after three years.

- Completely coated tanks with high performance coating
- Partially coated tanks with cathodic protection
- Preconstruction primer with cathodic protection
- Soft coatings with cathodic protection
- Rust tolerant epoxy coatings(Added after three years)

The initial report* published in 1982 and the project update report published in 1985 demonstrated that, of the systems evaluated, the inorganic zinc preconstruction primer with zinc anode cathodic protection was the best performer, least expensive initially and least expensive over the 20 year economic life of the ship. After five years of testing, this system continues to be the best performer. Partial coating with cathodic protection have performed as well as complete coating and are more cost effective. Soft coatings with cathodic protection failed in the first 90 days and was discontinued. The preconstruction primer with aluminum anodes failed after three years and was replaced by a rust tolerant, one coat epoxy system which is showing good results after two years of testing.

Certain prerequisites were also found to be necessary to assure successful cathodic protection performance, e.g. tanks must be "pressed up" with salt water ballast.

In conclusion, this project continues to achieve all project goals. Identification has been made of ballast tank corrosion protection approaches which are effective in mitigating corrosion and yet save both new construction and operating dollars. A final report, to include an updated economic analysis, is scheduled for publication in early 1988.

*Benjamin S. Fultz, "Cathodic Protection/Partial Coating versus Complete Coatings in Tanks," May 1982, NSRP #0158, A MarAd Sponsored Project.

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1. Conclusions

1.1 Project Results

The objective of this project is to evaluate the technical feasibility and economics of using a combination of cathodic protection and partial coatings in lieu of complete coating of ballast tanks with high performance coatings. Based on the results of initial data collection concerning probable system performances, a test program was formulated and approved by SNAME Panel SP-3. The originally approved test program evaluated four corrosion control alternates (See Table I for systems tested). After three years of testing, an additional technique was added. These are:

- Ballast tanks completely coated with high performance coatings (Baseline)
- Ballast tanks partially coated with high performance coatings plus cathodic protection
- Ballast tanks completely coated with soft coatings plus cathodic protection
- Ballast tanks preconstruction primed plus cathodic protection
- Ballast tanks coated with a rust tolerant epoxy coating

Both aluminum and zinc sacrificial anode systems were evaluated.

To test the proposed alternates, actual mock-up test tanks were constructed which duplicate ship ballast tank configurations. These tanks were then ballasted and deballasted for five years. At the end of each year, each alternate was graded. The present results of these tests are as follows:

- Preconstruction primer with a zinc anode has far exceeded the predicted performance. These tests indicate that this system is potentially a viable, cost effective strategy for the protection of salt water ballast tanks. This finding should be verified by an actual operational tank application.
- Zinc anodes outperformed aluminum anodes.
- Partial coatings with cathodic protection provided adequate corrosion protection.
- All anodes exceeded calculated performance.
- Soft coatings with cathodic protection failed after 90 days.
- Preconstruction primer with aluminum anode failed after three years.
- Completely coated tanks with high performance epoxy are exhibiting more failure than anticipated.

Simultaneous with the original test program, an economic analysis was performed based on available historical data. The final tank test results will be used to verify historical data and validate the economic analysis. An update of this analysis will be included in the final report.

1.2 Continued Research

The tank tests initiated as a part of this project should be continued for five additional years. At the present stage of the project, repairs should be made to those tanks which continue to demonstrate satisfactory performance. These are the completely coated tanks, partial coating with zinc anodes, and preconstruction primer with zinc anodes. The coatings systems with aluminum anodes should be replaced by two new systems to be selected by Panel SP-3. One possible candidate is a repeat of the rust tolerant epoxy coated tank. The coating should be applied over a "Power Tool Cleaned, SSPC SP-3" substrate and the resultant performance compared to the original completely coated tank (two coats of high performance epoxy) and the initial rust tolerant epoxy coated tank (one coat), both of which were applied over a substrate abrasive blasted to "Near White, SSPC SP-10."

The test tank configuration and site ballasting conditions of the test facility provide a unique, unequalled opportunity to predict service performance based on controlled tests. The continuation of this project coupled with the uniqueness of the test facility can be used to provide valuable performance data to the coating manufacturer, the engineering specifier, and end user of ship ballast tank corrosion control techniques.

2. Project Plan of Action and Results

2.1 Background Technical Information.

The original study and test program published in May 1982 contains a complete discussion of the pros and cons of each corrosion control technique and expected performance. Summarized below are the main points of that discussion.

2.1.1 High Performance Coating Systems

From collected data, high performance coating systems are projected to protect salt water ballast tanks for at least 10 years with 2% failure at 5 years and 5 to 10% failure at 10 years at which time the coating would be completely replaced. Tank 2, the tank which duplicates high performance coatings, is performing worse than predicted. After five years, this tank has 10 to 20% failure with some localized failure to 30%; however, no measurable metal loss has been detected to date.

2.1.2 Partial Coating of Tanks Combined with Cathodic Protection

Anode systems can be designed to protect steel from corrosion without replacement for at least four years in uncoated tanks and eight years in coated tanks.

As a general rule, cathodic protection systems do not perform satisfactorily on overhead surfaces due to air pockets. These areas are then subject to severe corrosion. Another problem associated with the use of cathodic protection in salt water ballast tanks is created from the residual water and wet silt left on the tank bottoms after deballasting. This salt muck provides a path for steel corrosion, but since the cathodic protection system (anodes) is above the surface of the muck, no protection is afforded.

To rectify these problems, high performance epoxy coatings are generally applied to the overhead surfaces to include 6" to 24" down each bulkhead and frame plus the tank bottoms to include 6" to 24" above the bottom. During ballast, the protective coating system protects the steel and supplements the cathodic protection system, thereby reducing anode consumption. During the deballasted cycle, the coatings protect the high corrosion areas. Test Tanks numbers 1 and 3 duplicate partial coating of tanks.

The test program for partially coated tanks supports an anode life of at least eight years for aluminum anodes and ten years for zinc anodes.

2.1.3 Preconstruction Primer Plus Cathodic Protection

Many shipyards automatically abrasive blast and prime structural steel prior to fabrication. This primer is normally removed and replaced by a high performance tank coating system.

If the tank coating system could be eliminated and the preconstruction primer left in place, many construction dollars could possibly be saved. Therefore, this approach was selected as a possible alternative for investigation. Sacrificial anodes were selected to provide the actual corrosion control mechanism. Inorganic zinc was selected as the preconstruction primer. Inorganic zinc primers provide the best shipbuilding handling and steel protection characteristics during construction. One major limiting factor of cathodic protection can be tank geometry. In these cases, primers could actually compliment the cathodic protection system by protecting overheads, bottoms, and small pocket areas. This point has been substantiated by the test program.

2.2 Tank Test Results

To verify the relative performance of each proposed alternate and the compatibilities between the cathodic protection and coating systems, three ballast tank assemblies (4' X 4' X 10') were fabricated from 1/4" A-36 steel plate and shapes. Each assembly consisted of three separate test tanks. (See Figure 2.2). Each tank was constructed to duplicate ship ballast tanks as concerns structure and configuration (See Figure 2.1). One side of each tank was of bolted construction to allow access for inspection.

Table I contains information on each tank as to corrosion control alternate; i.e., surface preparation, coating system anode type, etc.

Following tank fabrication and application/installation of each alternate, the tanks were ballasted and deballasted with fresh sea water. Table II contains data on the sea water used.

Each ballast cycle consisted of 20 days full and 10 days empty. Records were kept on sea water resistivity and cathodic protection half cell potentials. A copper/copper sulfate half cell was used for all potential measurements (see Table III). Due to a delay in the test program, the tanks were dry for nine months after the first year; therefore, the actual test period is greater than five years.

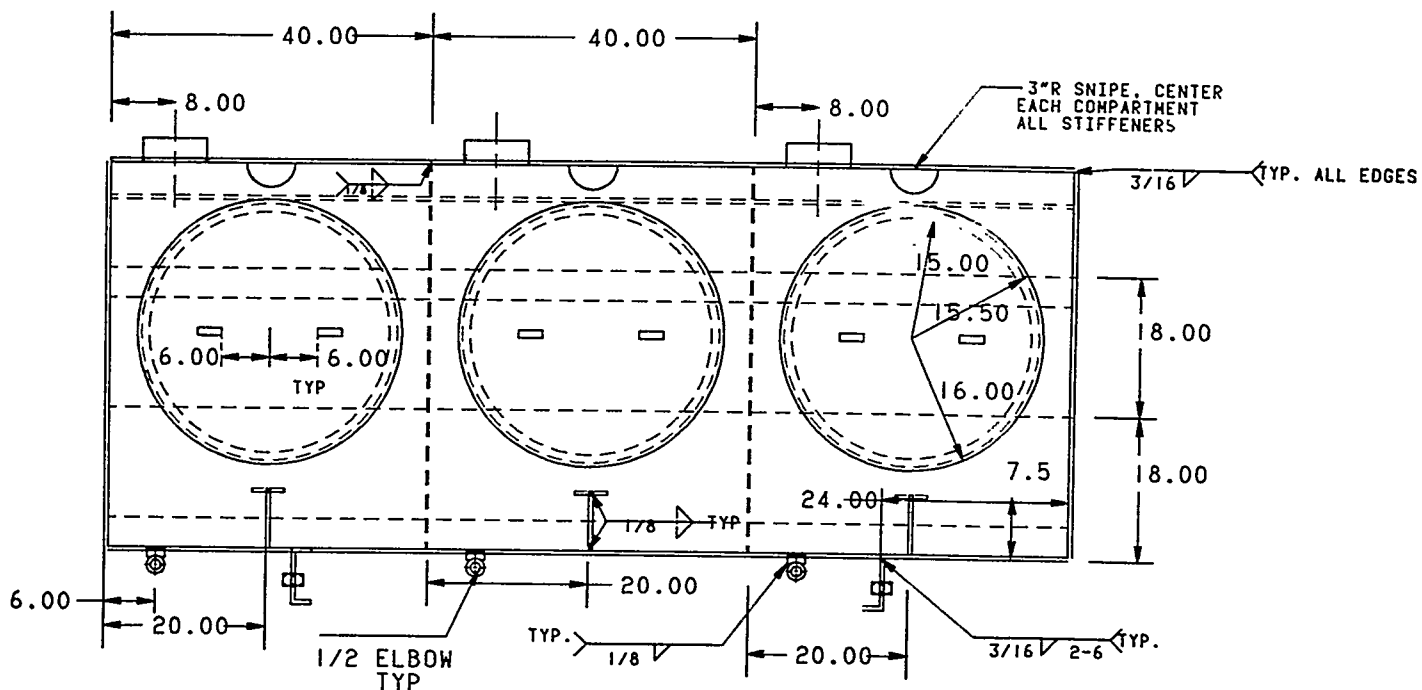


Figure 2.1: Drawing Showing Details of Test Tank Assembly

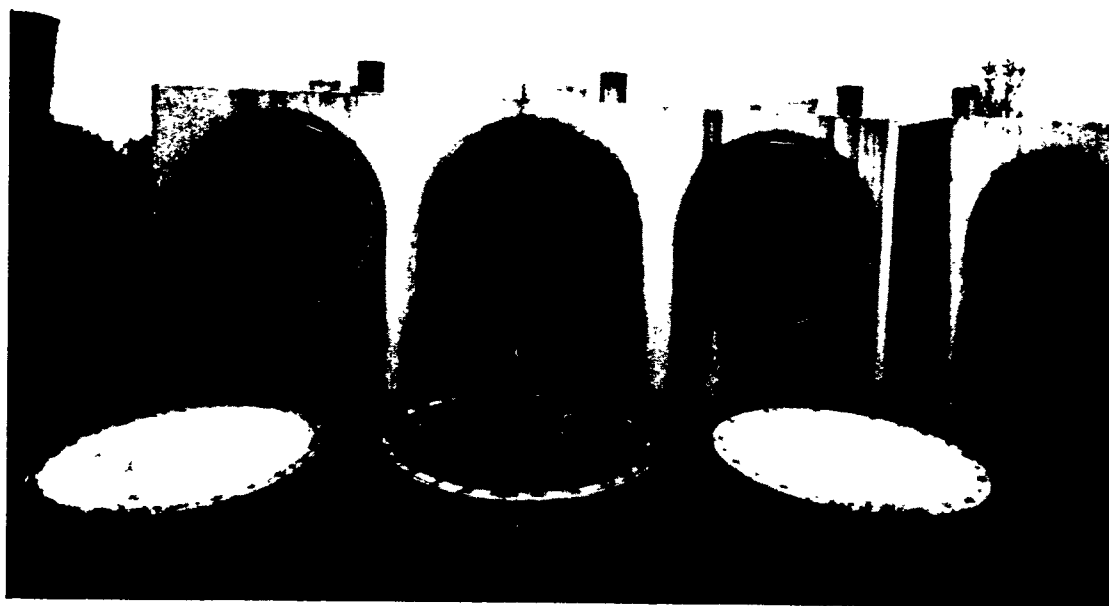


Figure 2.2: Photograph of Test Tank Assembly

Table I

Corrosion Control Alternates Used In Tank Test

Tank Number	Surface Preparation	Coating System	Film Thickness (MILS)	Anode Type
1	SP10	Two Coat Epoxy (MIL-P-23236) Partially coated - Top plus 6" down bulkheads and Bottom plus 6" up bulkhead.	6 - 10	Aluminum Alloy (Galvalum III)
2	SP10	Two Coat Epoxy (MIL-P-23236) completely coated	6.5-8.5	None
3	SP10	Same as Tank 1	6 - 9.5	Zinc (MIL-A-18001H)
4	SP10	Inorganic zinc preconstruction primer applied prior to fabrication	2.0	Aluminum (Galvalum III)
5*	SP10	Same as Tank 4	1.75-2.0	None
6	SP10	Same as Tank 4	1.8	Zinc (MIL-A-18001H)
5	SP10	Rust Tolerant Epoxy (Test Initiated in 1985)	15-17	None

* Replaced after three years with new system.

2.2.1 Performance of Aluminum Anode with Partial Coatings

At the completion of five years ballasting and deballasting, the entire uncoated area is rust colored. The calcite deposit seems more porous and loose than previously noted. Removal of the calcareous deposit showed rust under the deposits. Where the deposit had delaminated, the area left exposed had rusted. See Figure 2.3. It was also noted early in the experiment that the deposit formed by the aluminum anode was more coarse and less tenacious than the zinc produced deposit. No significant amount of steel loss has been noted in tank 1 (See Table IV), even though there is some metal loss on the edges of structural members. The coating on the flat bottom is an ASTM Rust Grade 2 (33% Failure). The coating on the tank sides is an ASTM Rust Grade 5 to 6 (1 to 3% Failure). The overhead coated area has an area of approximately 1.5 square foot which is totally failed. The balan-

ce of the overhead area is an ASTM Rust Grade 9 (0.03% Failure). The aluminum anode is approximately 60% depleted. This system continues to protect the tank steel.

2.2.2 Performance of Completely Coated Tank.

Figure 2.4 is a graphic representation of the performance of the paint system in Tank 2. The main failure points are in the weld areas and along the top of the roof flange. The overall breakdown of the coating is judged to be between 10 and 20% percent with some localized areas to 30%. As stated earlier this system is performing under expectations. There is no metal loss except for minor flange faces. The coating system continues to provide protection.

2.2.3 Performance of Zinc Anode with Partial Coatings

The color of the bare portion of the tank surface is primarily the color of the calcareous deposit. See Figure 2.5. Removal of the deposit revealed tight black oxide under the film. Where the deposit had been removed, a new deposit has formed. The calcareous deposit in Tank 3 is more dense and tenacious than that formed with the aluminum anode; however, the deposit was observed to be more porous than previously reported. No metal loss was measured and the tank continues to be protected. No blisters in the tank were detected. This system appears to be superior to the system in Tank 1 which uses an aluminum anode. The coated flat bottom of the is an ASTM Rust Grade 5 (3% Failure). The coated tank sides are an ASTM Rust Grade 8 (0.1% Failure), and the tank top is an ASTM Rust Grade 9 (0.03% Failure).

2.2.4 Aluminum Anode with Preconstruction Zinc Primer

Early in the test cycle, the aluminum anode seemed to protect the zinc coating and even built up a calcareous deposit on bare welds and other damaged areas. At the end of three years, the calcareous coating was depleted. After five years, the inorganic zinc coating is depleted as predicted in the last report. See figure 2.6. The measured anode potential was still sufficient to protect the steel; however, the anode is almost depleted. Rust scale was visible on the overhead surfaces; however, there is no appreciable metal loss on the tank sides. (See para. 1.3)

2.2.5 Performance of Preconstruction Primer Only

Initially, a calcareous deposit was formed on welds and damaged areas; however, with time this deposit disappeared (approximately 9 months). At the end of the twelfth cycle, all of the zinc primer was used up and the steel was just beginning to rust. After thirty-six ballast cycles, the tank was beginning to lose metal. Heavy, uniform rust was present. This coating was replaced after three years with a rust tolerant epoxy coating (see paragraph 2.2.7).

2.2.6 Performance of Zinc Anodes with Preconstruction Primer

This continues to be the best performing system tested. A calcareous deposit formed on all the surfaces after the second cycle. These deposits are still present after five years. Figure 2.8 are photographs of this system. Note the deposits on the weld area. Minor corrosion is visible on the overhead area primarily due to air pockets. Some areas on the tank flat bottom subjected to erosion from the ballast water filling operation are beginning to corrode.

2.2.7 Performance of Rust Tolerant Epoxy Coating

The original preconstruction primer only system was replaced by a one coat rust tolerant epoxy coating system which was previously tested and shown to have promise in another MarAd sponsored research project(Rust Compatible Coating). The tank required abrasive blasting prior to coating application because of the heavy rust scale which had formed in this tank. After two years this system is providing excellent protection with an overall ASTM Rust Grade of 9 (0.03% Failure). Some localized areas have a Rust Grade of 8 (0.1% Failure).

Table II

Test Site Sea Water Information

Water Resistivity ranged from 26 to 29 ohms/cm

	SPRING		SUMMER		FALL		WINTER	
	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>
Water Temperature (oC)	17.0	20.0	26.5	30.0	17.0	30.5	14.5	25.0
pH	6.5	7.5	7.6	8.3	6.7	8.1	7.2	8.2
Oxygen (Dissolved)	5.8	8.5	4.2	7.8	4.2	7.6	5.2	9.4
Salinity (parts per 1000)	17.5	29.0	21.5	35.5	6.0	33.0	8.5	27.0

Table III

Half Cell Potentials (Cu/CuSO ₄)								
(All Potentials Are Negative)								
<u>Tank Number</u>	<u>FIRST CYCLE 1HR</u>	<u>SECOND CYCLE 24HR</u>	<u>THIRD CYCLE</u>	<u>FIFTH CYCLE</u>	<u>EIGHT CYCLE</u>	<u>TWELFTH CYCLE</u>	<u>Thirty-Sixth CYCLE</u>	
1	0.77	1.01	1.05	1.03	1.03	1.04	1.05	1.002
2	0.96	0.98	0.96	0.92	0.85	0.67	0.57	0.644
3	0.80	0.98	1.01	0.96	0.90	1.02	0.94	0.982
4	0.99	1.07	1.09	1.05	1.06	1.06	1.01	0.957
5	0.95	0.96	0.71	0.69	0.71	0.70	0.65	0.767
6	0.97	0.99	1.02	0.97	0.96	0.98	0.90	0.928

Table IV

<u>Ultrasonic Steel Thickness Readings (Inches)</u>					
<u>Tank 1</u>	<u>Tank 2</u>	<u>Tank 3</u>	<u>Tank 4</u>	<u>Tank 5</u>	<u>Tank 6</u>
0.270	0.270	0.270	0.245	0.255	0.270
0.265	0.270	0.270	0.260	0.245	0.270
0.250	0.270	0.255	0.250	0.245	0.270
0.245	0.270	0.270	0.255	0.245	0.270
0.250	0.270	0.245	0.255	0.250	0.270
0.255	0.265	0.250	0.250	0.245	0.275
0.265	0.265	0.245	0.260	0.255	0.270
<u>0.265</u>	<u>0.270</u>	<u>0.250</u>	<u>0.265</u>	<u>0.245</u>	<u>0.270</u>
0.258	0.268	0.257	0.255	0.248	0.271 (Aver)

2.2.8 Comparison of Ultrasonic Steel Thickness Readings

Table IV contains the measurement data on steel thicknesses after five years of testing. The steel used to construct the test tanks all came from the same heat. Tanks 1,2 and 3 measurements were actually made on the same steel plate. The measurements were made at designated areas on the outside back of each tank. A single plate was used to fabricate the back of all the tanks in this series. Likewise, the backs of tanks 4,5 and 6 were constructed from the same plate. Tanks 1 and 3 have almost the same average thickness; whereas, Tank 2, the completely coated tank, has a higher reading; This could mean that the completely coated tank is providing somewhat better protection as concerns overall metal loss. The first two and the last two readings in Tanks 1 and 3 were made over the coated areas. The other readings in this series were made over the cathodic protected areas. Interestingly, Tank 5, the tank which failed totally after less than three years has the lowest readings (most metal lose). This Tank has since been recoated. The preconstruction primer in Tank 4 has also failed and only the aluminum anode is providing protection. Tank 6, the best performer to date, shows the least metal loss.

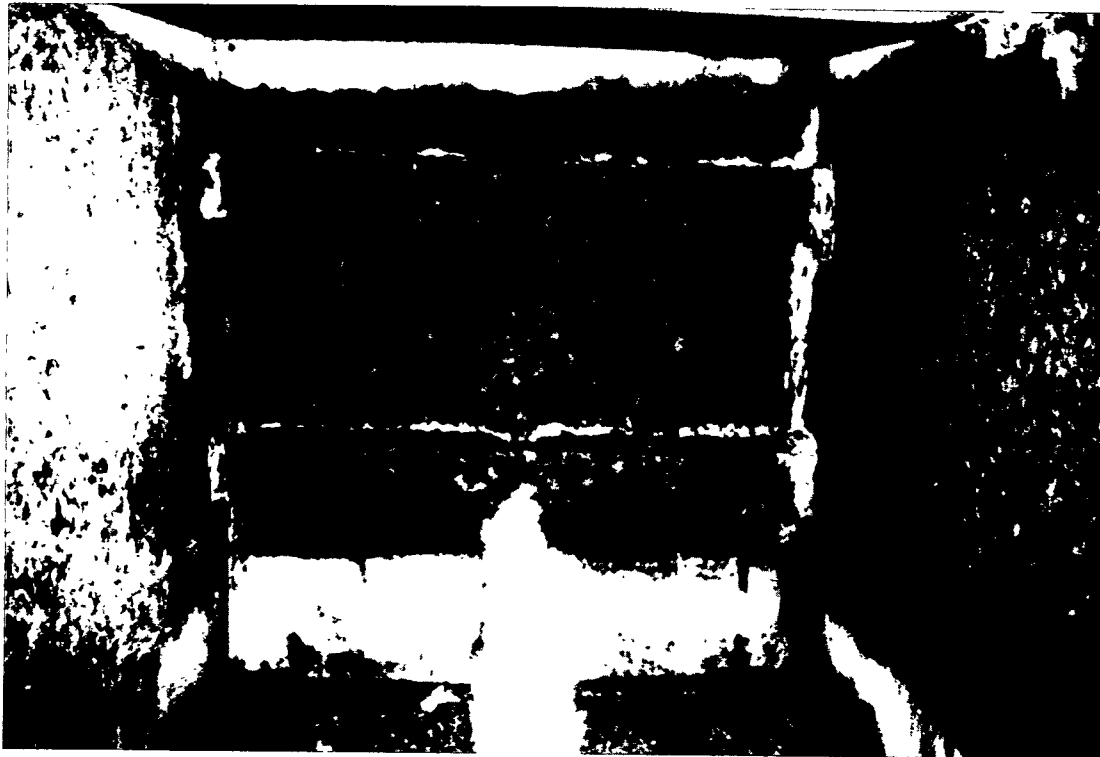
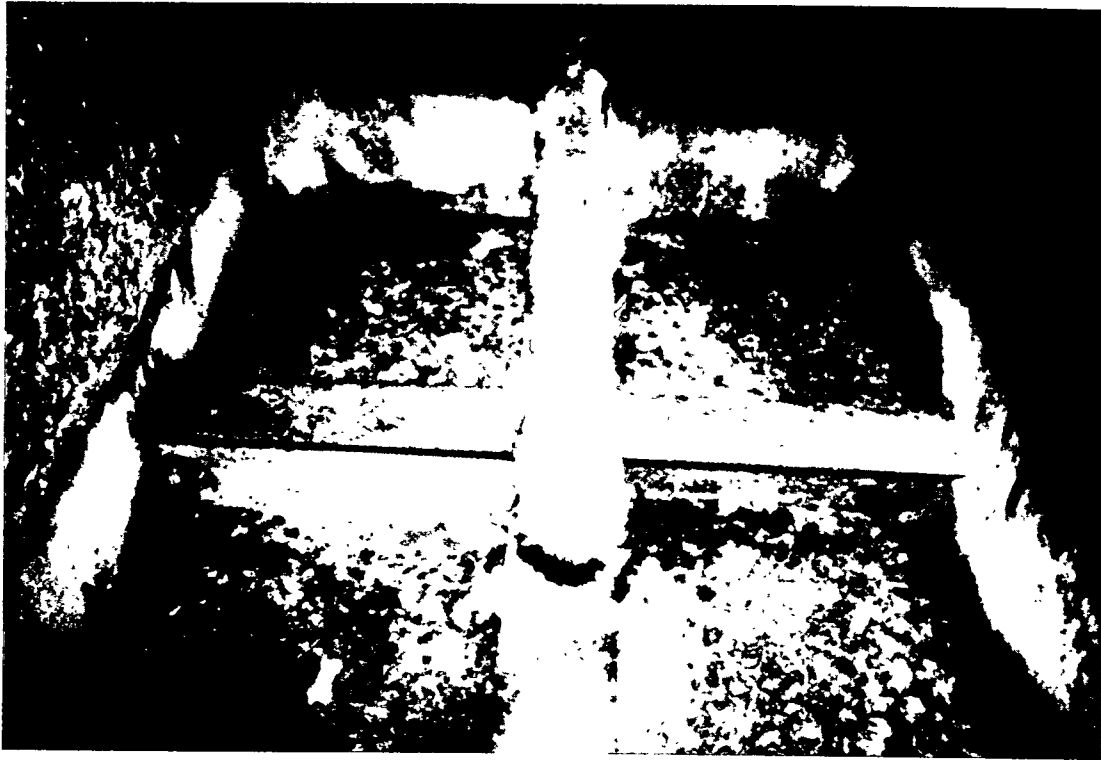


Figure 2.3: Aluminum Anode/Partial Coating After Five Years

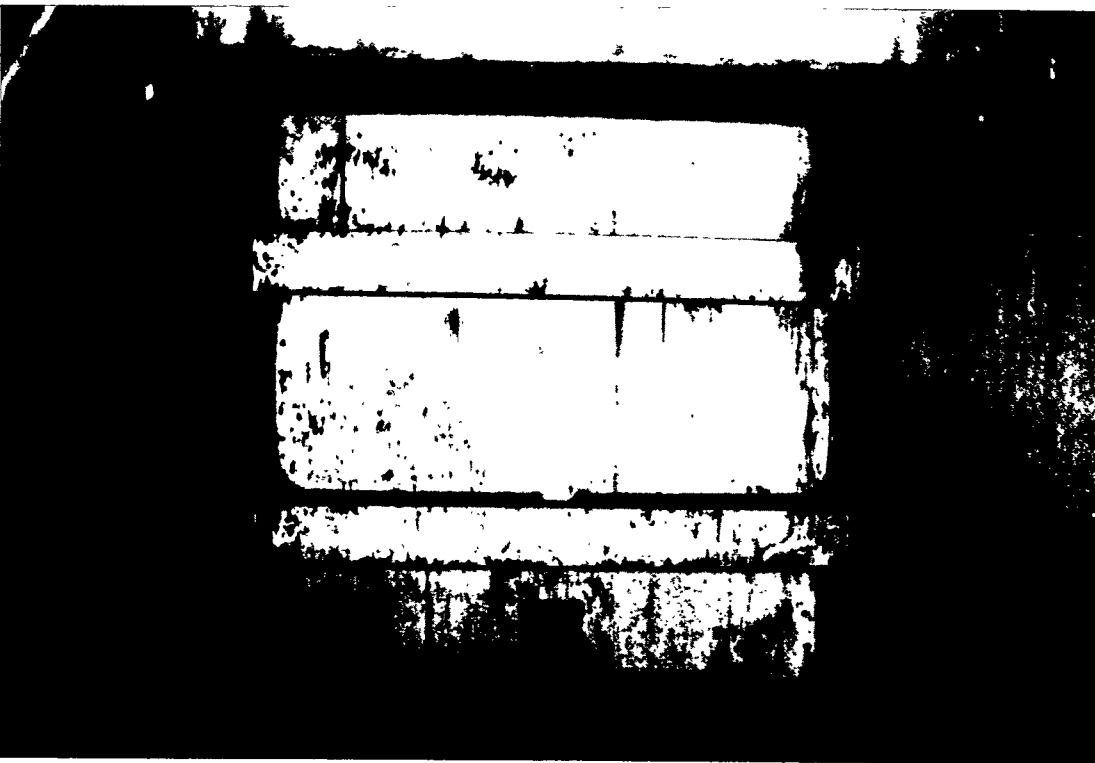
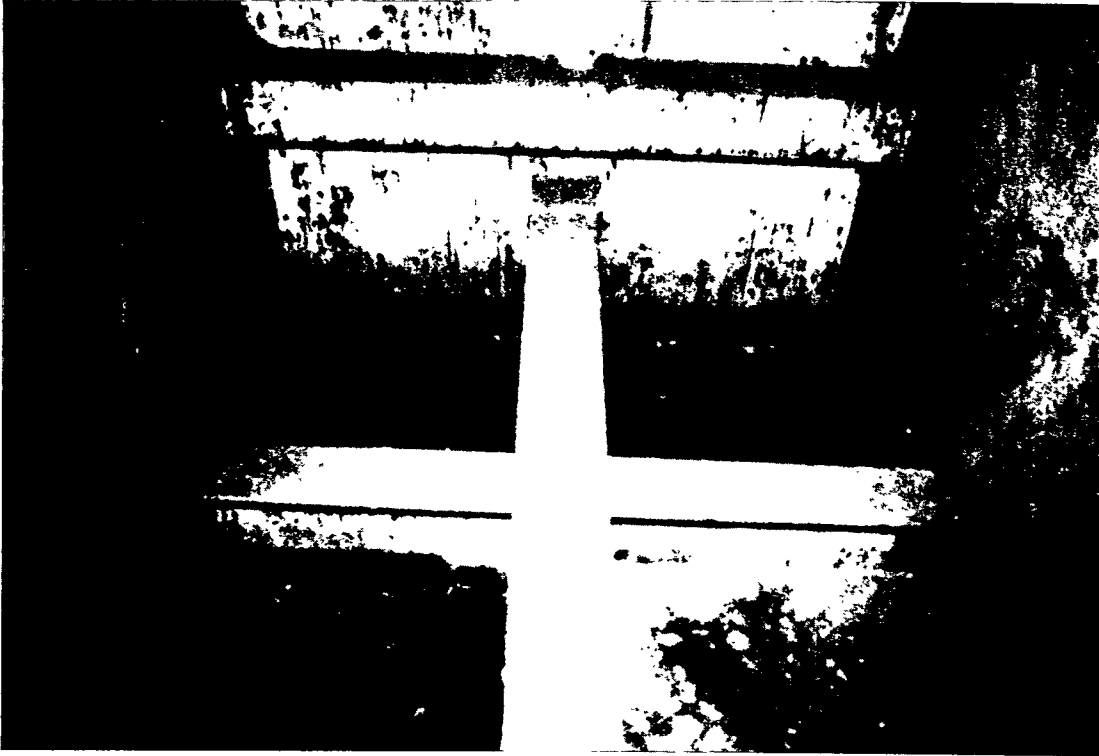


Figure 2.4: High Performance Coating After Five Years

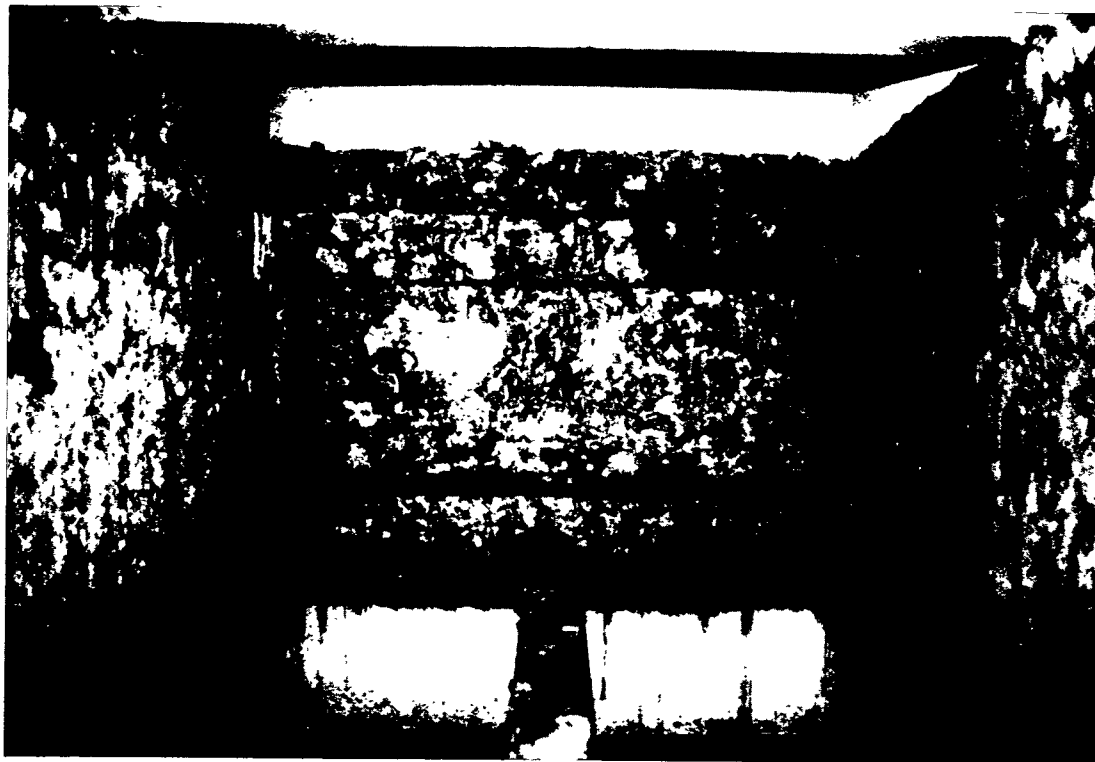
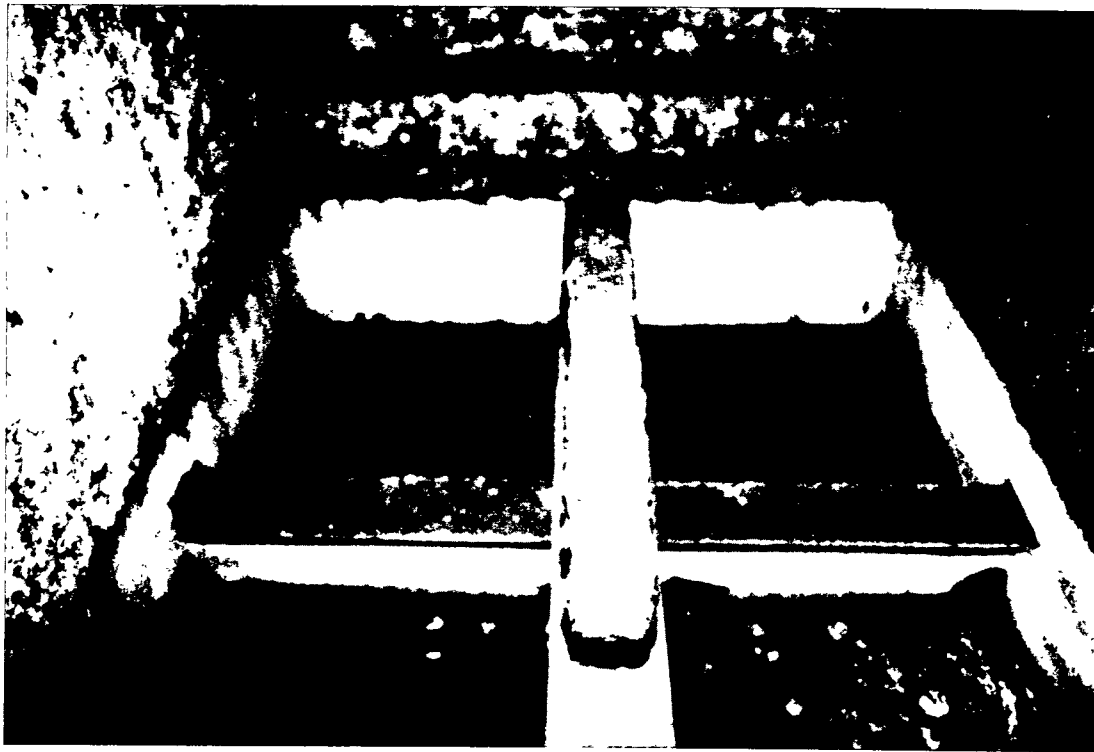


Figure 2.5: Zinc Anode/Partial Coating After Five Years

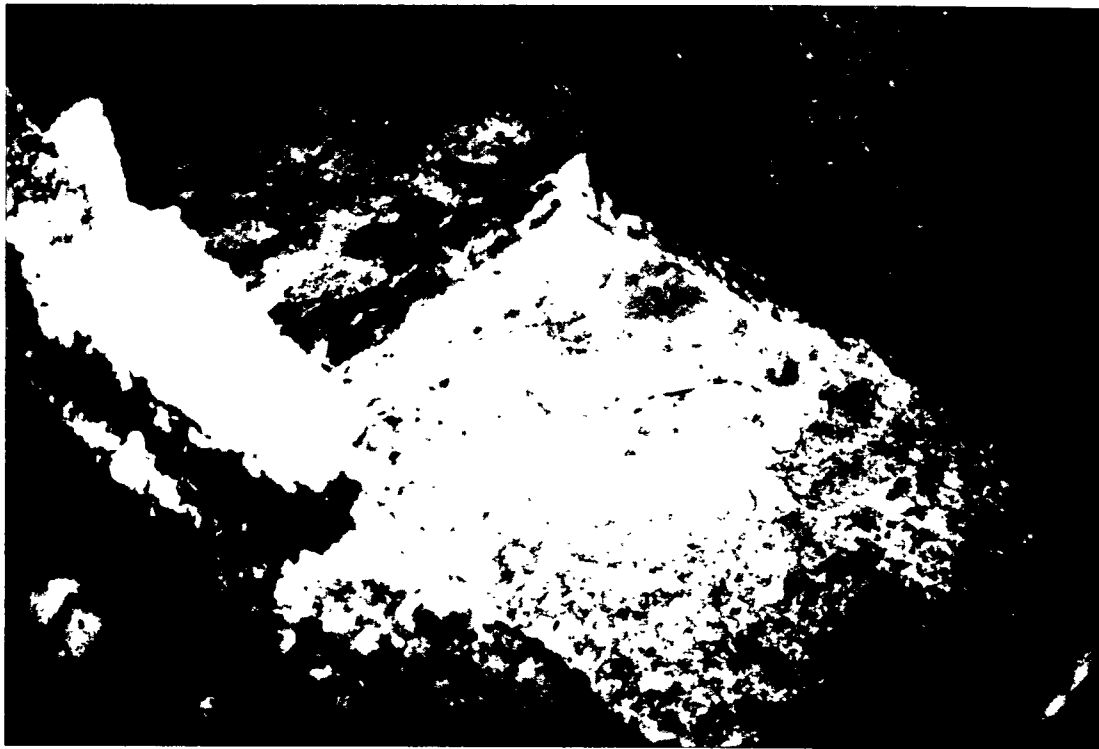


Figure 2.6: Zinc Primer/Aluminum Anode After Five Years

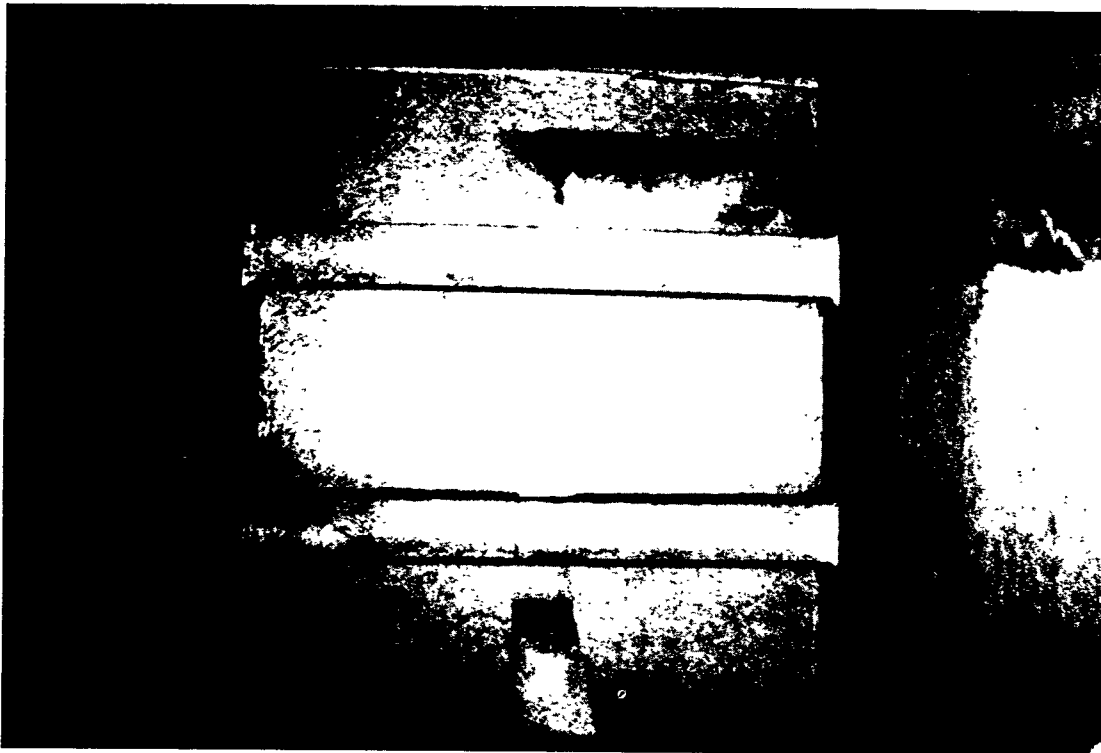
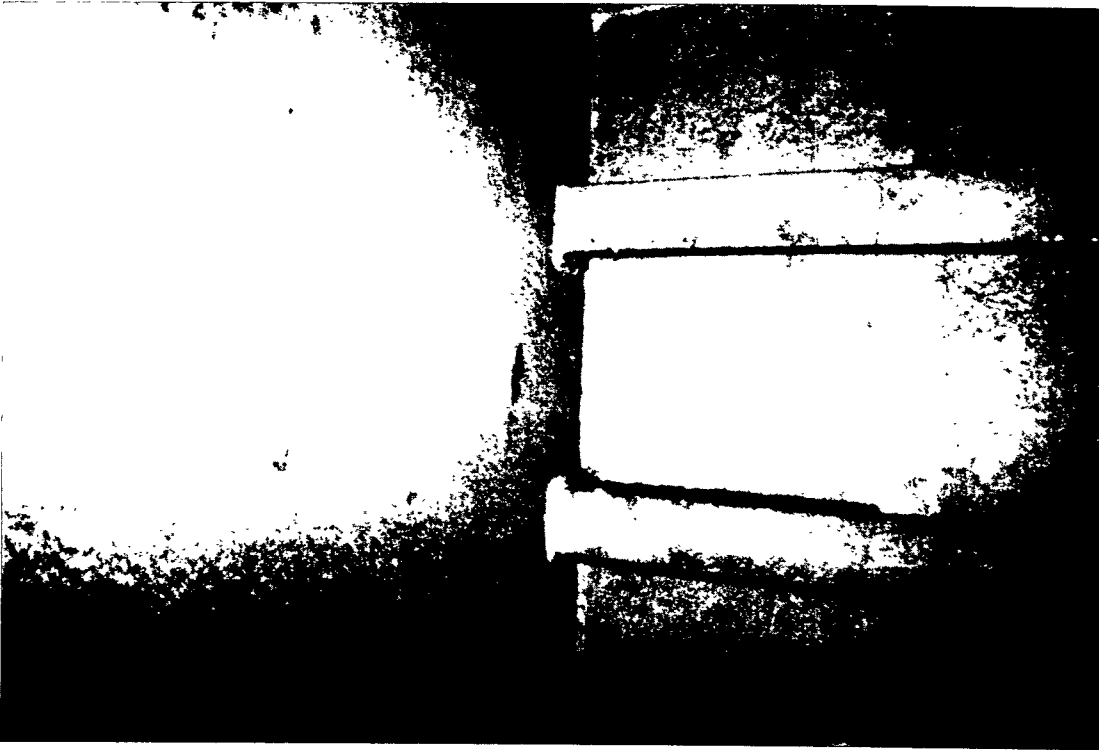


Figure 2.7: Rust Tolerant Epoxy After Twenty-four Cycles

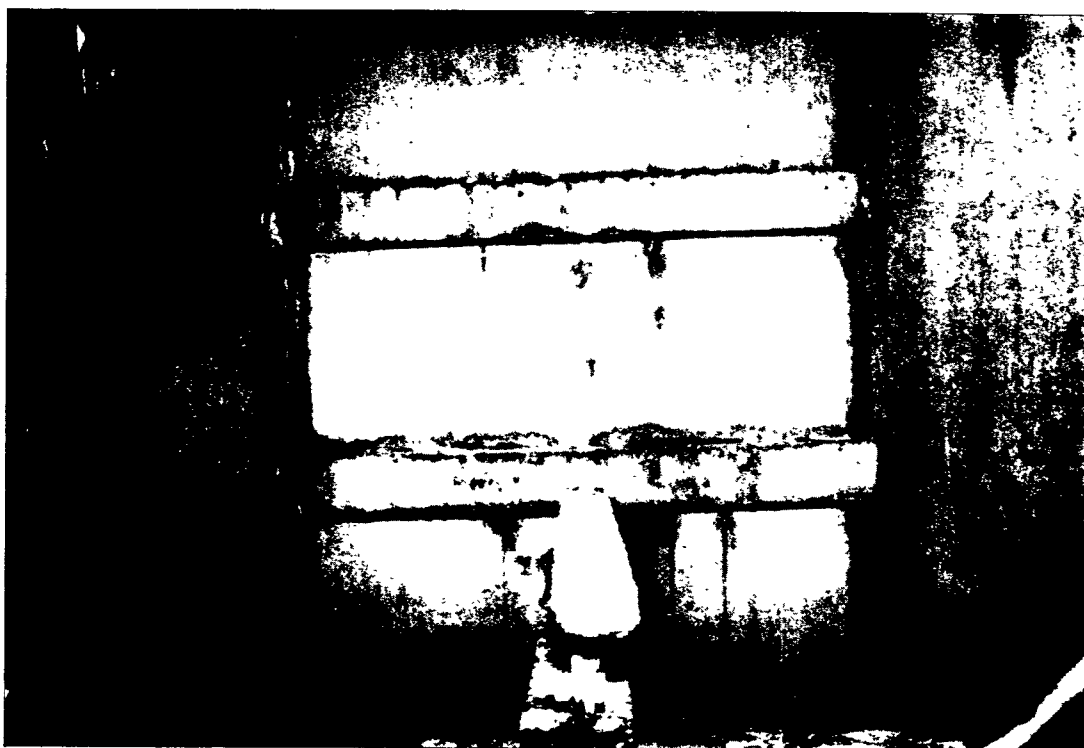
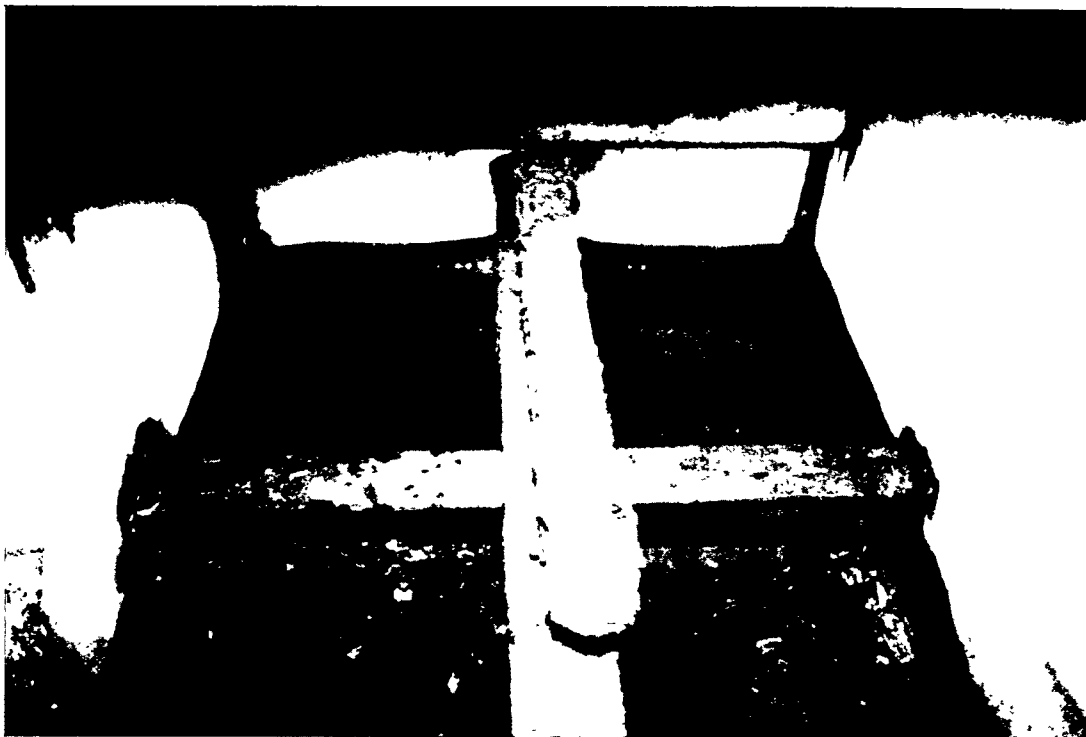


Figure 2.8: Preconstruction Primer/Zinc Anode After Five Years

2.3 Anode Performance

Prior to discussing actual anode performance, it is necessary to calculate anode requirements. Table V lists the basic design characteristics of the anodes used.

Table V
Basic Properties of Anodes in Sea Water

<u>Anode Type</u>	<u>Current Capacity (Amp-Hr/Lb)</u>	<u>Consumption Rate (Lb/Amp-Yr)</u>	<u>Potential</u>
Zinc (Mil-A-18001H)	372	23	-1.01
Aluminum (Galvalum III)	1150	7.6	-1.08

In addition, two other facts must be known. The first is the required current density to protect the steel in the intended service. For segregated ballast 14 milliamps for uncoated areas and 1 milliamp for coated areas are the generally accepted values. The second is the sea water resistance which, for the test, was 26 to 29 ohms. The following equation can be used to calculate required anode weights:

$$W = \frac{A \times D \times F \times Y \times 8760}{I \times S \times 1000}$$

Where:

- A = Surface area to be protected in ft²
- D = Required current density
- F = Factor which represents percent immersion time as a decimal
- Y = Design life in years (Usually 4)
- I = Anode current capacity (Amp-Hr/Lb)
- S = System efficiency (Normally 85%)
- 8760 represents the number of hours in a year

This equation gives the actual total weight of required anodes; however, a minimum number of anodes must also be calculated based on anode current output.

The following examples will help to understand how the test anode requirements were calculated:

TANK 1- Aluminum Anode with Partial Coatings

$$\text{Surface Area Coated} = 63 \text{ ft}^2$$

$$\text{Surface Area Uncoated} = 46 \text{ ft}^2$$

Required Current Density

$$\text{Coated Area} = 1 \text{ milliamp/ft}^2$$

$$\text{Uncoated Area} = 14 \text{ milliamps/ft}^2$$

Immersion Factor = 0.6 (60% Ballast Time)

Design Life in Years = 5

System Efficiency = 0.85 (85% Efficient)

Anode Current Capacity = 1150 Amp-Hr/Lb (From Table V)

From the equation, the required anode weight can be calculated:

Where: $W_{\text{Total}} = W_c + W_n$

W_c = Weight required for coated area

W_n = Weight required for uncoated area

$$W_c = \frac{63 \text{ ft}^2 \times 1 \text{ milliamp/ft}^2 \times 0.6 \times 5 \text{ Yr} \times 8760 \text{ Hr/Yr}}{1150 \text{ Amp-Hr/Lb} \times 1000 \text{ milliamps/amp} \times 0.85}$$

$$W_c = 1.69 \text{ Lbs}$$

$$W_n = \frac{46 \text{ ft}^2 \times 14 \text{ milliamps/ft}^2 \times 0.6 \times 5 \text{ YR} \times 8760 \text{ Hrs/Yr}}{1150 \text{ Amp-Hr/Lb} \times 1000 \text{ milliamps/amp} \times 0.85}$$

$$W_n = 17.31 \text{ Lbs}$$

$$W_{\text{Total}} = 1.69 \text{ Lbs} + 17.31 \text{ Lbs} = \underline{19.0 \text{ Lbs}}$$

Actual anode selected for the test was a stock 20 Lb anode.

TANK 3- Zinc anode with partial coatings

$$W_{Total} = W_c + W_n$$

$$W_c = \frac{63 \text{ ft}^2 \times 1 \text{ milliamp/ft}^2 \times 0.6 \times 5 \text{ Yr} \times 8760 \text{ Hr/Yr}}{372 \text{ Amp-Hr/Lb} \times 1000 \text{ milliamps/Amp} \times 0.85}$$

$$W_c = 5.24 \text{ Lbs}$$

NOTE: The only difference between this calculation and the one for aluminum is the anode current capacity (372 versus 1150).

$$W_n = \frac{46 \text{ ft}^2 \times 14 \text{ milliamps/ft}^2 \times 0.6 \times 5 \text{ Yr} \times 8760 \text{ Hrs/Yr}}{372 \text{ Amp-Hr/Lb} \times 1000 \text{ milliamp/Amp} \times 0.85}$$

$$W_n = 53.52 \text{ Lbs}$$

$$W_{Total} = 5.24 + 53.52 = 58.76 \text{ Lbs}$$

One standard 50 Lb anode was selected.

Now that the anode requirements for each tank have been calculated, the same equation can be used to calculate projected annual anode consumption. This data can be compared to the actual measured weight loss of each anode used in the test program.

Table VI lists the calculated theoretical projected anode consumption rates for each tank plus the actual weight loss for each tank tested.

TABLE VI
Anode Performance Summary (5 Years)

<u>Tank Number</u>	<u>Anode Type</u>	<u>Theoretical Weight Loss at 100% Efficiency (lbs)</u>	<u>Actual Weight Loss (lbs)</u>
1	Aluminum (Galvalum III)	19.0	11.0
3	Zinc (MIL-A-18001H)	58.8	22.5
4	Aluminum (Galvalum III)	N/A*	16.0
6	Zinc (MIL-A-18001H)	N/A*	16.0

*The above formula does not apply for porous metallic coatings.

Three conclusions can be drawn from the results contained in Table VI:

- All anodes performed better than projected
- Zinc anodes outperformed aluminum anodes
- Zinc anodes and inorganic zinc primer performed the best of all systems tested
- Aluminum anodes are suspect of causing blistering after three years in epoxy coated Tank 1.

One probable explanation of the increased anode performance was the calcareous deposits formed on bare areas. Once formed, the anode demand decreased, therefore slowing consumption. Because the zinc anode created a calcareous deposit which was more dense and tenacious, less of the deposit was removed during ballasting. Again, reduced bare areas reduced anode consumption. Zinc anodes have also been reported in the literature as being more dependable and reliable than aluminum anodes. After two years of testing, the static test condition of the test tanks were questioned. The argument was presented that the calcareous deposit was not subjected to the erosion action of water movement in the tank due to ship roll during ocean movement. In an attempt to provide some duplication of the phenomenon, the tanks were opened at the end of each cycle and loose materials removed with a garden hose spray. No difference in performance was detected.

In the tank with inorganic zinc preconstruction primer with zinc anode, no detectable amount of zinc primer was depleted during the test with the exception of the area within an air pocket at the top of the tank. The weight loss of the zinc anode was such that the system would theoretically continue to protect for fifteen years with no anode replacement. The aluminum anode in the zinc primed tank is almost totally depleted.

In summary, the zinc anodes outperformed the aluminum anodes for the given test conditions. In all cases, the anodes performed better than the 85 percent projected efficiency.